Department of Mechanical Engineering

ME-492: Research Project – II

Design and Fabrication of Intake and Exhaust Manifold of a Prototype Race Car

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A Thesis On

Design and Fabrication of Intake and Exhaust Manifold of a Prototype Race Car

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<u>CERTIFICATE</u>

This is to certify that the work done by Kaushal Kishor in this thesis entitled “Design and Fabrication of Intake and Exhaust Manifold of a Prototype Race Car”, has been carried out under my observation in partial fulfillment of the desires for the grade of Bachelor of Technology in Mechanical Engineering during session 2014-2015 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of my knowledge, this work has not been give in to any other University/Institute for the honor of any degree or diploma.

Dr. Saroj Kumar Patel

(Supervisor)

Associate Professor

Department of Mechanical Engineering

Preface

I would like to be grateful to the Project guide Prof. Saroj Kumar Patel for his great involvement concerning the project from the time of its initiation. His permission has helped me work in the workshop in the late hours in the workshop while manufacturing the model.

I would like to thank Navin Kumar, Shaikh Tariq Mobin, and Gaurav Chaudhary for their support in the workshop and assistances to help me design the model.

This Project would also not have been a fruitful without help of N. Mithun Babu, Basir Khan Manabendra Rout, Surajit Barad and Debendera Pradhan. Also, I am beholden to all the members of Team ROADRUNNER for facilitating me in my project.

Also, I couldn't have completed without substantial assistance of Pankaj Kumar Vaikunth Bhai Katariya, Vijay Kumar Singh, Vishes Ranjan Kar, Sushree Sasmita Sahoo and Anshuman Dash.

Not the least, I would like to thank my classmates, other colleagues and entire college environment for their support and entrusting me with the project and finalizing this project within the limited period.

Finally, I couldn't forget appreciable moral support of my mother, father, brother Bhartendu Kumar and Himanshu Kumar and all my family members in accomplishing this work.

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Abstract

Increasing interests in automobile of this generation has increased motor sports. Resulting in increased number of racing events held year long. In this paper an approach for designing, analyzing and manufacturing of air intake and exhaust system is discussed for prototype model of a Formula style car with the locally available resources in hand as per the rules specified by the two major student level events organized in India. It also gives a brief introduction to the flow simulation of the designed models in SolidWorks for various rpm for tuning the engine and practical noise testing of newly designed exhaust system for the prototype car powered by 600 cc engine of Yamaha R6 YZF. These competitive events require a restrictor on the passage of air to the engine and also require noise emissions below 110dB with the exhaust system.

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Symbols Used

A	Cross sectional Area of the Runner
BDC	Bottom Dead Centre
c	Constant
ECD	Effective Cam Duration
f	Frequency of Helmholtz Resonator
L	Length of the Runner
RV	Reflective Value
TDC	Top Dead Centre
v	Velocity of Sound in Air
V	Volume of Plenum

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Chapter 1
Introduction

1.1 Introduction

In this generation, motor sports has become one of the major area of interest of millions of people across the globe. This has lead path for different organizations to available motor sports events all over the world. It may be of different kind like- speed oriented plain road vehicle or all-train vehicle, economic fuel oriented or based on any other criterion. It has challenged engineers to overcome all the hurdles for achieving this.

In India, there are such two major student level events (SUPRA and FDC) available for formula-style race car. The concept behind such an event is to contract a design team for development of a small Formula-style race car that will be manufactured by a fictional manufacturing company after satisfactorily fulfillment of required goals. This prototype car will be judged for its quality and standard so that it may be a better market product. The possible marketing group for this race car will be amateur autocross racers or will be used to train formula one drivers of learner phase. Participants of these competitions are collage students. Such cars are designed and manufactured by them only and tested on the event site whose purpose is to promoting better problem resolving technique.

Many rule constraints of such events has defined restricted parameters on which design must be capable of saving every bit of horsepower and bring out better performance and fuel economy of same engine. Air intake and exhaust system are some of those fields where there is lots of scope of gaining extra power.

A possible air intake and exhaust manifold for such a prototype model (single seat race car) was intended to design, analyze and manufacture with the locally available resources in hand as per the rules specified by the two major student level events organized in India. This race car was powered by 600 cc engine of Yamaha R6 YZF. Also, study of various systems that are available and relevant design procedure adopted in this field was done. This designing wouldn’t have been be succeeded without continuous analyzing and simulating the model of the designed system. This analysis was done by both analytical as well as experimental procedures.

1.2 Motivation

The FSAE team TEAM ROADRUNNER of NIT Rourkela selected YAMAHA R6 YZF engine for both Formula Student 2015 and SUPRASAE 2015.This engine was a 4 cylinder, 600cc displacement, 4 stroke engine from a motorcycle. The choice to continue using the R6 engine was made for several reasons.

Firstly, the team has only one engine and in order to switch to a different engine, the team would need to purchase new engine and again we have to start our tuning from beginner's stage for new engine. And also buying a new engine and its accessories at a significant cost was anyhow not a good idea.

Secondly, the engine in a formula SAE car needs several custom designed subsystems in order to be functional. These include the oil system, fuel system, cooling system, as well as all of the electrical components. In order to switch to a new engine, each of these subsystems would need to be carefully redesigned at a large expense of the team's time and resources. The FSAE team decided the most benefit would come from building on the team's current knowledge of the R6 engine and strive to create an entire engine package that pushes this engine to its full potential.

Thus, for the selected engine an intake system with restrictor and exhaust system has to be designed with minimum cost and resources available locally in order to get better performance out of same engine.

1.3 Aim of the present work

It was intended to design an intake and exhaust system which satisfied the required rules of these competitive events in order to make engine in working condition:

1.3.1 Intake Manifold:

The following rules to be surveyed by designer to design intake manifold of above mentioned car:

a. All parts of the air intake system must confine in the volume created by joining straight line from each tire to the top most portion of the roll bar and the base of the car.

b. For safety purpose power of engine is reduced by placing a circular restrictor in between throttle body and the plenum of the air intake system. This restrictor will be the only passage for all air flow to the engine.

c. Restrictor diameter for different types of fuel, which should be maintained for each event during competition are
   - Gasoline - 20.0 mm
   - E-85 – 19.0 mm

d. Placing a restrictor would vary air flow rate while response of engine wouldn't be same. Thus, tuning the engine according to the new air intake configuration is required to get better performance of the engine.

1.3.2 Exhaust Manifold:

The following rules needed to be monitored in order to design exhaust manifold of such prototype car:

a. Configuration should be such that in any case driver shouldn't be subjected to smoke.
b. The exhaust extension should be less than 60 cm in height with respect to ground and less than 45 cm measured towards rear of the rear axle.
c. If any portion of exhaust system lies in front of the main roll hoop, it should be covered enough to avoid hot surface to the person coming towards the car or to the driver.
d. The noise test of the engine will be done when car will be in rest position and also mandatory that gear lever is not engaged. Device used to measure sound level will be a free-field microphone, which will be placed about (0.5-1) m behind the exhaust outlet without any obstruction in between them. In case of multiple exhaust, the previous test procedure will be followed for each outlet and the maximum reading will be taken into account.
e. Engine revolution which will provide an average piston displacement of 914.4 m/min will considered for the required noise test general automobiles and 731.5 m/min for the engines used for industrial purpose.
f. The required test engine speed will be governed by the event committee, and highest permissible sound level is 110dB.

Chapter 2
Literature Review

2.1 Literature Review

Air intake and exhaust system of an engine plays very important role in engine performance in such competitions where even a slight less performance increases chances of failure. So, designing those needs special attention and lots of study. In market there are various manufacturer like - Eurojet MK6 Exhaust System, SFX, Donaldson, and Silex, which provides wide range of these system according to performance requirements.

Claywell *et al*. [1] investigated different types of general intake configuration used in such competitive events. The Conical-Spline Intake system was found to give less variation of volumetric efficiency when compared to every cylinder and engine performance out of all the three types of intake concepts that were evaluated. Han-chi and Hong-wu [2] suggested different ways of optimization technique used for air intake and exhaust system. Orthogonal Array Testing was implemented which is common these days for designing air intake of such competitions. It was assumed that the air in the system due to its inertia is sloshing back and forth and bouncing in the resonant cavities as a result expansion and compression waves are passing through the pipeline, which gets reflected due to collision with open and closed ends and also due to variation in cross sectional area of the pipeline, Hartmen and Jeff [3]. The engine performance of a JIALING JH600 motorcycle was optimized by applying energy balance equation for the whole system and mass balance in different section of the engine. Also, it was found that the solution for simulation of 1-D flow in the approximated direction considering average of flow, requires the conservation of mass, momentum and energy equations, Delaney and Michael [4].

Murray *et al*. [5] have designed a tri-Y exhaust system for an engine powered by Honda CBR 600 RR. In this design primary header coming out of first valve is joining with the header of the last one in the series. And, the two middle order primary headers join similarly. After that both two secondary headers join to make a single header through which a muffler/silencer will be connected. Due to less number of sharp edges in the air intake design avoiding and due to its' sleek design there was less turbulent flow of air to each valve of the cylinder. Therefore, this new air intake reduces the starvation of fresh air to each of the cylinders. A flush bell-mouth design on the entrance to the runners was used which greatly enhances the mass flow rate into the plenum and reduces the chances of creation of vacuum pockets. But, this type of air intake manufacturing will be done by either reinforcing a rapid prototyping/3D printing or by casting which will be not possible everywhere [6].

John Wall, [7], provided a brief interpretation of the dynamics of exhaust system of an internal combustion engine which makes it requisite field for improving performance of the engine by both theoretically and practically. Dynamic analysis of exhaust system, theoretical modelling and simulation, experimental investigation product development and virtual prototypes were studied. And a distinctive exhaust configuration was modelled, simulated and experimentally investigated for realizing the fact and to appraise modelling ideas. In this investigation prime attention was to observe the effect of the bellows-type flexible joint.

Kennedy *et al*. [8], have designed exhaust and intake system for a car which has 600cc Suzuki GXR engine. This was designed to meet the criterion to satisfy the rule of 20mm restrictor on the intake flow of air to the engine. A new engine mapping was done for better performance of the engine. It also compared the air flow simulation using CFD analyses and looked at various alternate air intake configuration. It discussed use of rapid prototype technique for creating a prototype. And presented designing and manufacturing of a new throttle body. The whole process for engine ECU tuning and dyno test results were also introduced. This presented an approach for the designing and analyzing of various exhaust configuration and measuring sound level.

A simple way of designing an air intake for an engine which is going to be tuned according to requirements is to considering different configurations of air intake with different plenum volumes and then choose a particular. It is a basic requirement to have a tuned plenum volume and runner length for new mapping of ECU. Accordingly models can be rejected with no plenum and different runner lengths also the one which provides option for tuning plenum volume only. Final selection would be such that it provides tuning of the runner lengths and allows a slight modification for changing the plenum volume.

Chapter 3
Methodology

3.1 Intake Manifold:

This air intake manifold was designed on the concept of Helmholtz Resonator. The colligation of plenum and runners in the air intake system makes a Helmholtz Resonator [9]. A typical configuration of air intake having plenum (cavity) of volume *V*, runner of length *L* having an opening (in the cavity) of cross sectional area *A*, forms a Helmholtz resonator. A basic Helmholtz resonator can be understood as a pen cap which is when blown it produces sound of a distinct frequency. This sound is effect of to and fro movement of air particle through the passage of the pen cap. Similarly, if the air pressure wave timing synchronizes with the intake valve opening in the intake header, the air will be drawn into the combustion chamber itself instead of suction created by the piston movement which creates an increment of the power output from the engine. The distinctive frequency of a Helmholtz resonator is given in equation (1).

$$.f = \frac{c}{2\pi}\sqrt{\frac{A}{V*L}} \qquad (1)$$

where, v = speed of sound in air,

A = cross sectional area of the intake runner,

L = length of the intake runner, and

V = volume of the plenum.

For compensation of viscous effect in the intake headers, the velocity of sound in air is often multiplied with a constant which is lesser than1.

3.1.1 DESIGN GOALS:

1. To design an air intake sub system to give engine proper induction at power band rpm (6000-8000).
2. To provide optimum low end torque and power.
3. To accommodate the standard restrictor rule along with no compromise of torque and power output from the engine.

3.1.2 ITEMS TO BE CALCULATED AND DESIGNED:

3.1.2.1 Runner length

3.1.2.2 Optimum plenum volume (both theoretically and practically)

3.1.2.3 Choosing of the optimum ram venture flow and accommodate choked flow

A proper design of the air intake is necessary to use the induction waves generated by the engine for obtaining best performance rather than feeding the air directly to the engine which reduces the efficiency without the proper geometry.

The first step for designing air intake is the calculation of proper runner length

3.1.2.1 RUNNER LENGTH CALCULATION

For any rpm and runner diameter, the optimized intake runner length can be calculated for a given rpm and tube diameter is calculated by assuming the fact that in between valve opening and closing the pressure wave travels four times back and forth. The effective cam duration (ECD) is calculated using the formula given in equation (2).

$$ECD = 720 - (\text{Adv. duration} - 30) \qquad (2)$$

Since the pressure wave is required to arrive before the valve closes and after it opens hence a cam duration of 20 to 30 degrees is subtracted.

The data of valve timing duration for the concerned car engine is given in the Table 3.3.1.

Table 3.3.1 Valve timing duration

Intake Valve Timing	**Angles(°)**
Open before TDC	39
Close after BDC	65
Duration	284

Hence,

$$ECD = 720 - (284 - 30) = 466$$

The Formula for optimum intake runner length is given by equation (3).

$$L = \frac{EDC*0.25*v*2}{RPM*RV} - \frac{D}{2} \qquad (3)$$

where:

ECD = Effective Cam Duration

RV = Reflective Value

D = Runner Diameter (in inches)

v = Velocity of air in ft. /sec

We have calculated the runner length at 8000 rpm using the second set of pressure wave (RV=2)

$$L = \frac{466*0.25*1300*2}{8000*2} - \frac{0.394}{2}$$

$= 475.85$ mm

3.1.2.2 DETERMINATION OF OPTIMUM PLENUM VOLUME

We tested plenum of three different volumes 2.4*l*, 3.6*l* and 4.2*l*. Since our runner length came out to be 475 mm; hence to sync with the volume of runner, we finalised our plenum volume to be 3.6*l*. If we had taken a 4.2*l* volume plenum, it would have decreased the low end power. We tried to implement bell- mouth because it creates a static pressure without disturbing the nearby runners unlike the direct end system

3.1.2.3 CHOOSING OF OPTIMUM RAM VENTURE FLOW AND ACCOMODATE CHOCKED FLOW

Schematic diagram of a ram venture flow for an air intake system is shown in figure 3.1.2.3.

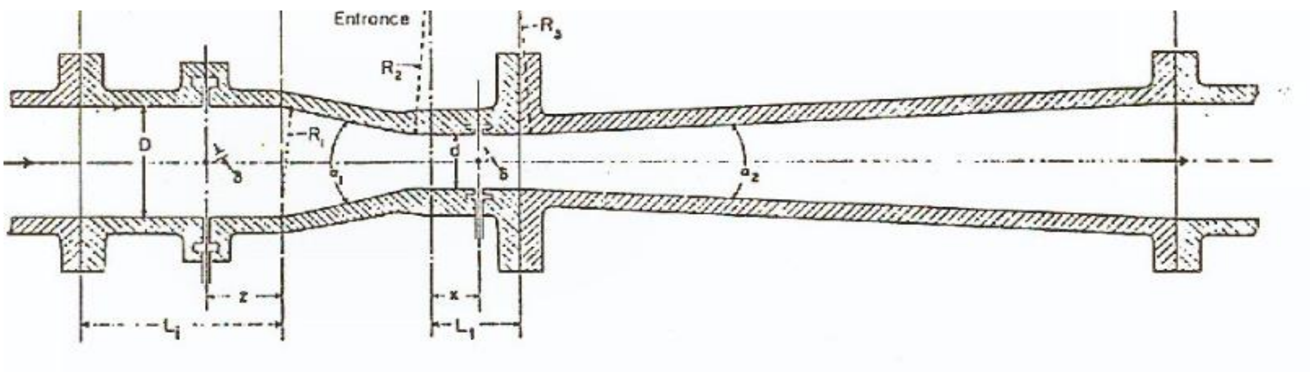

Figure 3.1.2.3 Schematic diagram of Ram venture

After calculation final values obtained of the parameters shown in figure 3.1.2.3 were as follows:

$$L_1 = 36.5\ mm \text{ or } L_1 = \frac{36.5}{4} + 254 = 262.89\ mm$$

$$Z = \left(\frac{36.5}{2}\right) \pm \left(\frac{36.5}{4}\right) = 27.22\ mm \text{ or } 8.98\ mm$$

$$R1 = (1.375 * 36.5) = 50.29\ mm$$

$$R_2 = (3.625 * d) \pm (0.125 * d) = 74.93\ mm \text{ or } 69.85\ mm \qquad (\text{where } d = 20\ mm)$$

$$5d \leq R_3 \leq 15d \quad \rightarrow \quad 100 \leq R_3 \leq 300$$

$$a_1 = (21 \pm 1)\ degrees = (20\ or\ 22)\ degrees$$

3.1.3 DESIGN:

Air intake was designed in SOLIDWORKS for the concerned car. Figure 3.1.3(a), (b), (c), (d) respectively shows front, side, isotropic and rendered view of the air intake. Air intake was designed as top/centre feed air intake with bent runners.

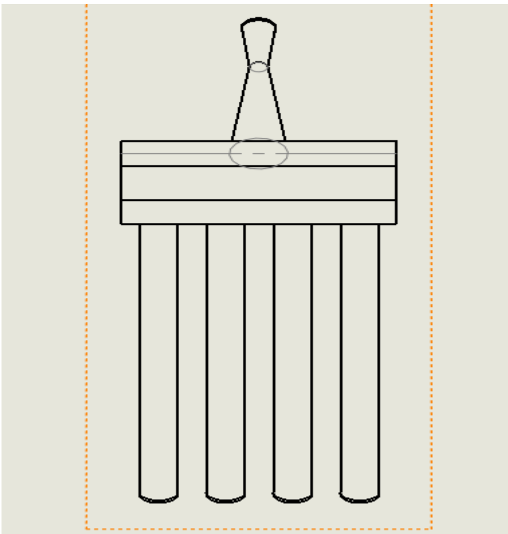

Figure 3.1.3 (a) Front view of designed intake manifold

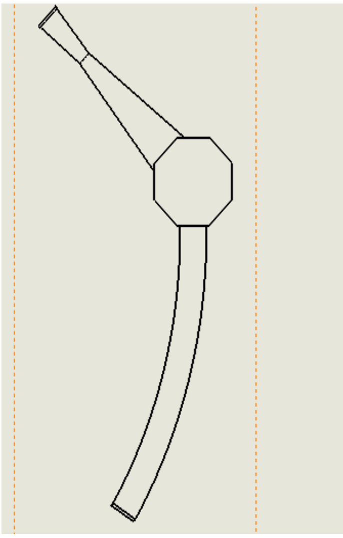

Figure 3.1.3 (b) Side view of designed intake manifold

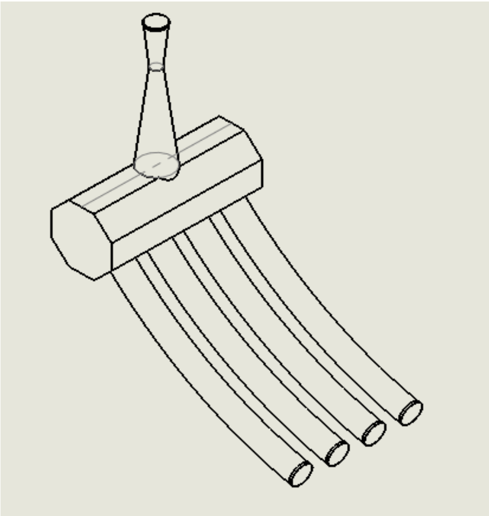

Figure 3.1.3 (c) Isometric view of designed intake manifold

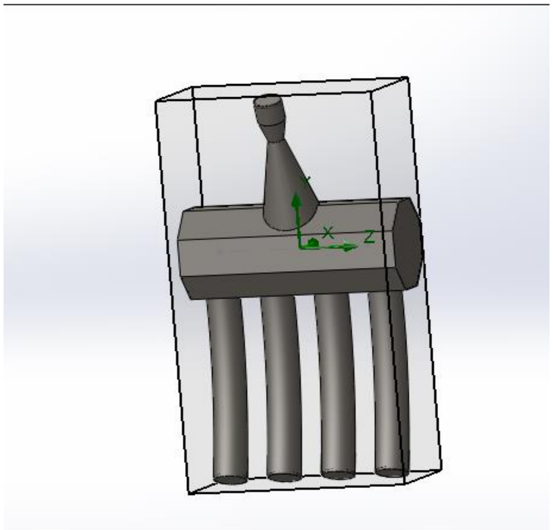

Figure 3.1.3 (d) Rendered view of designed intake manifold

3.2 Exhaust Manifold

3.2.1 Design Consideration

Exhaust plays a crucial role in the performance of any internal combustion engine. Its unreasonable limitation of flow can result in extra fuel consumption, increased exhaust temperature and smoke. It also results in decrement of exhaust valve life. It is mandatory to maintain a specific limit of back pressure in exhaust system else it will increase emissions. Exhaust system should be designed keeping in mind the allowable back pressure will be half of the maximum permissible. Restriction of backpressure is generally due to pipe size, silencer, and system configuration.

A sophisticated design like a Tri-Y (or 4-2-1 Configuration) could be chosen but manufacturing would not be possible everywhere. Thus, a box type arrangement was chosen which was easy to manufacture, time saving and also cost efficient. Here, exhaust coming out of combustion chamber enters a box passing through separate compartment in it. It was assumed that high velocity smoke particle on entering in the box chamber gets reflected in several direction such that it will interfere with particles coming out of each pipe. Geometry of box was designed such that fraction of particle of each pipe interfere with the other one, resulting in extra sound reduction. The second model was designed such that the smoke coming out of each pipe gets reflected in the direction of exit of the chamber. The designed two models are shown in figure 3.2.1.1 and 3.2.1.2.

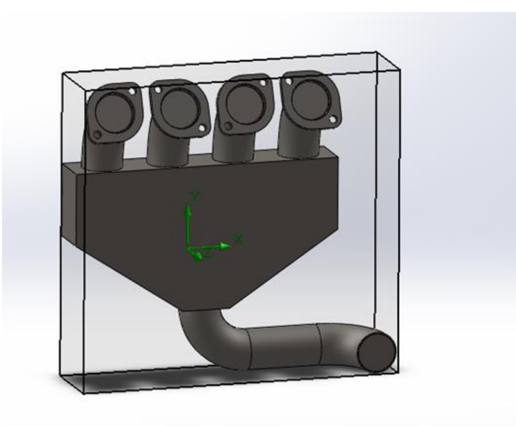

Figure 3.2.1.1 Exhaust manifold model 1

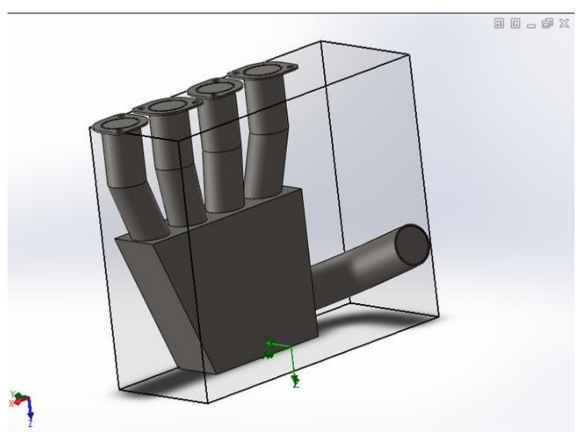

Figure 3.2.1.2 Exhaust manifold model 2

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3.2.2 Noise Test Setup:

The noise test of the engine will be done when car will be in rest position and also mandatory that gear lever is not engaged. Device used to measure sound level will be a free-field microphone, which will be placed about (0.5-1) m behind the exhaust outlet without any obstruction in between them. In case of multiple exhaust, the previous test procedure will be followed for each outlet and the maximum reading will be taken into account. Engine revolution which will provide an average piston displacement of 914.4m/min will considered for the required noise test general automobiles and 731.5m/min for the engines used for industrial purpose.

The required test engine speed will be governed by the event committee, and highest permissible sound level is 110dB. Noise test of the exhaust system was done at the competition site that demanded noise emissions should be below 110dB at approx. 11000rpm. The setup for noise testing was as shown in Fig 5. The test results gave a reading of 103dB at approx. 11000rpm which was well within the formula student requirements. The noise test set up for model1 and model2 is shown in figure 3.2.2.1 and 3.2.2.2. respectively.

Figure 3.2.2.1 Noise test setup for model 1

Figure 3.2.2 2 Noise test setup for model 2

Chapter 4

Results and Discussions

Solid models of the designed air intake and exhaust system was created in solid works and analyzed in flow simulation applying fixed boundary conditions. The simulation was done for each valve separately and also combined average effect was analyzed for various rpm. After analyzing the simulation of model for various rpm and given boundary condition, the results for pressure, temperature and velocity variation runner for the optimum rpm range (6000-8000) have been displayed below for designed model of intake manifold in figure 4.3 to figure 4.15. And, for corresponding rpm pressure, temperature and velocity variation in exhaust manifold of designed model1 and model2 is given in figure 4.16 to 4.45

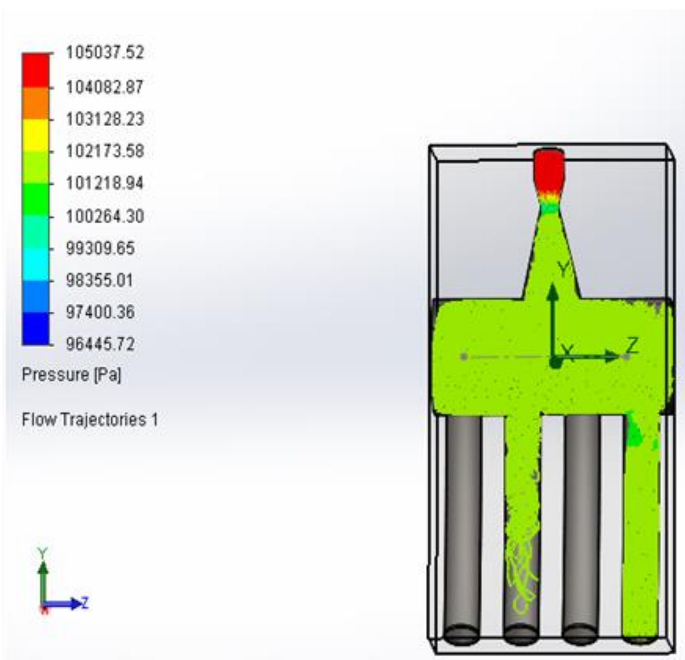

Figure 4.2 Pressure variation in runner1

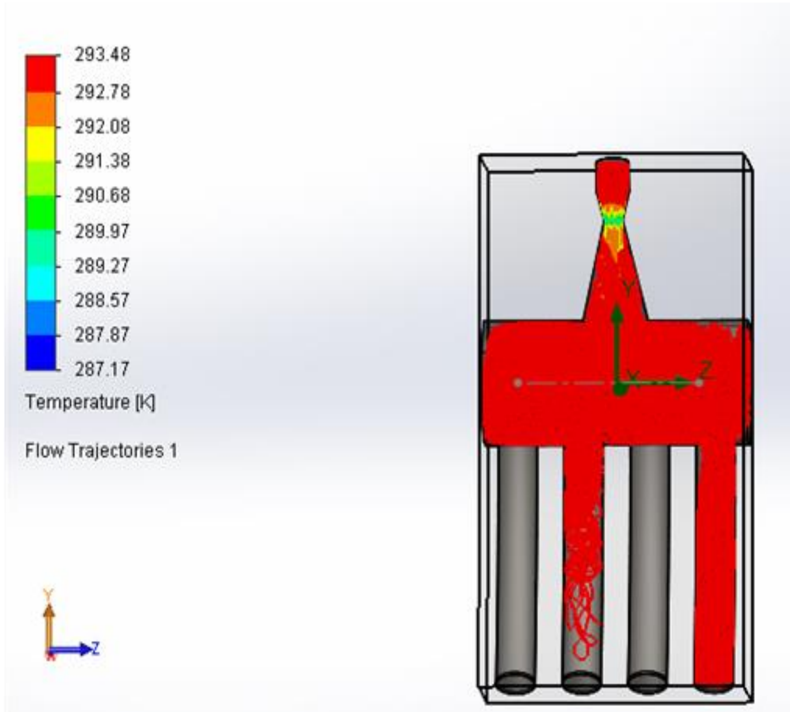

Figure 4.2 Temperature variation in runner1

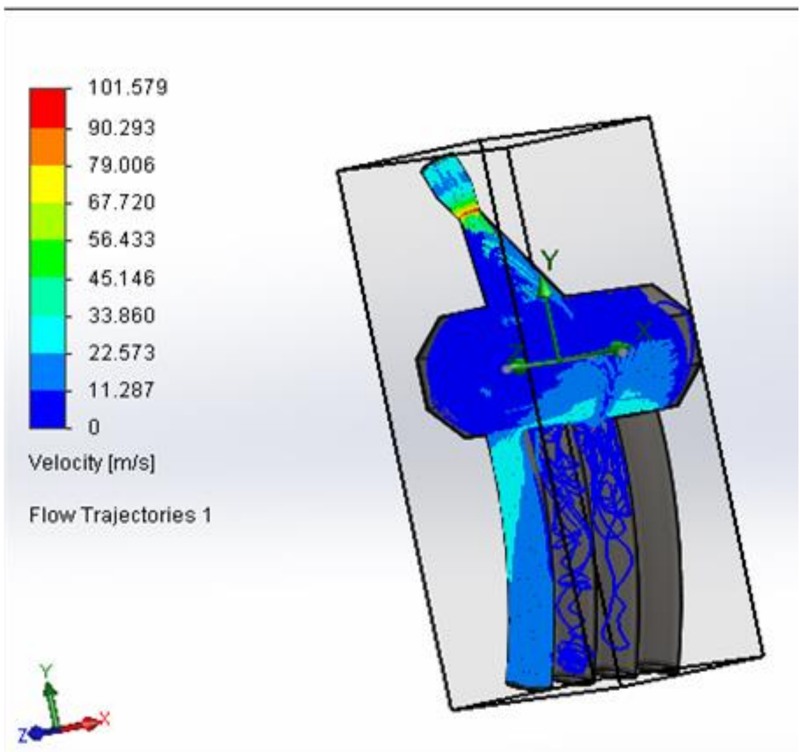

Figure 4.3 Velocity variation in runner1

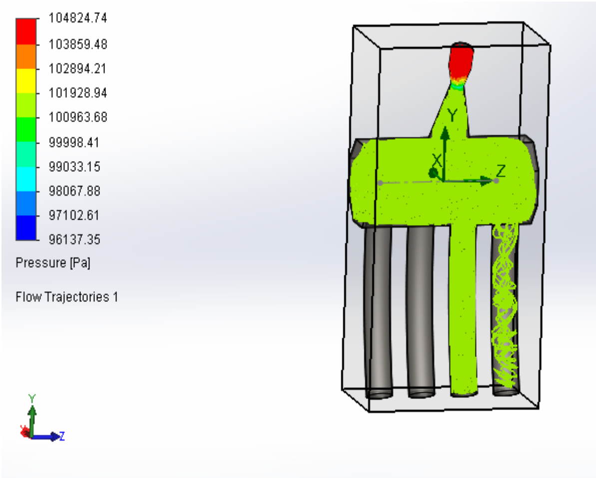

Figure 4.4 Pressure variation in runner2

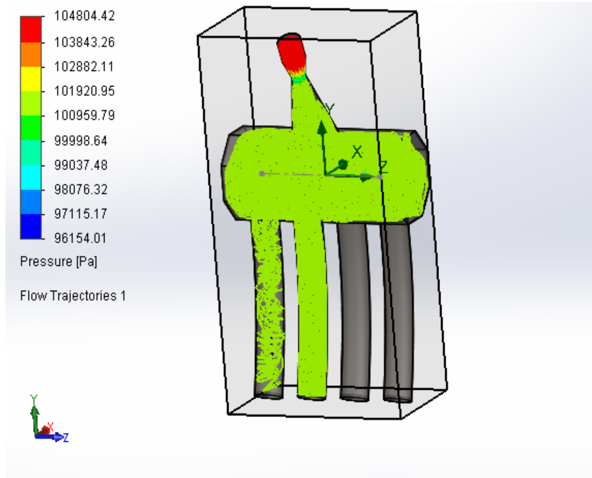

Figure 4.5 Pressure variation in runner3

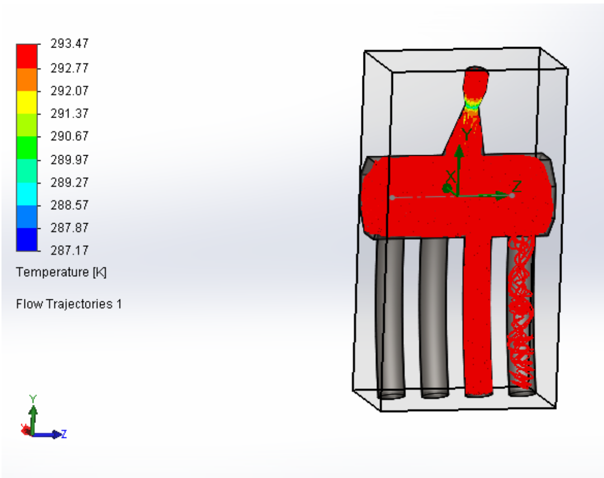

Figure 4.6 Temperature variation in runner2

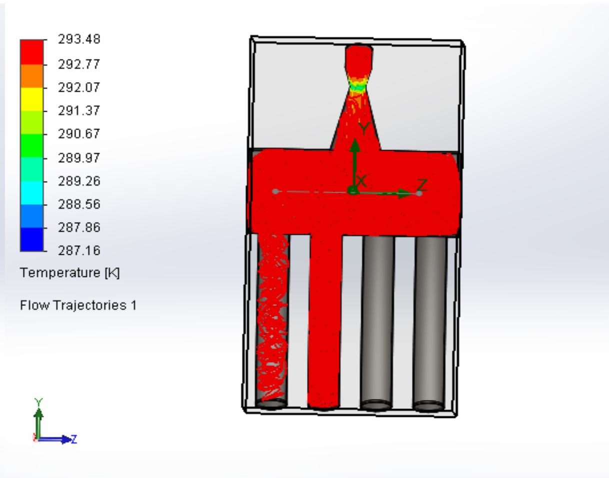

Figure 4.7 Temperature variation in runner3

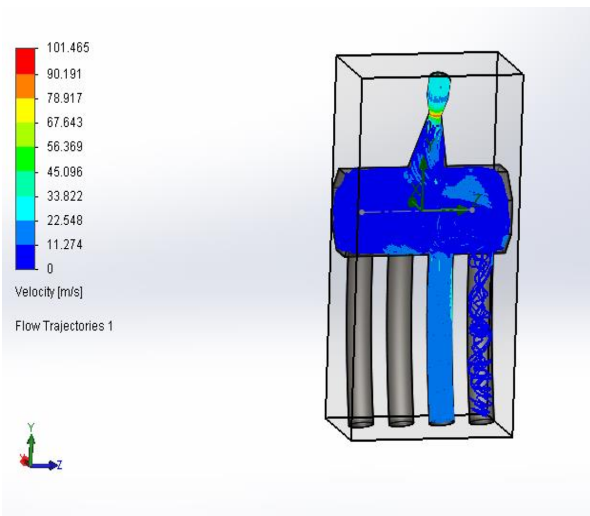

Figure 4.8 Velocity variation in runner2

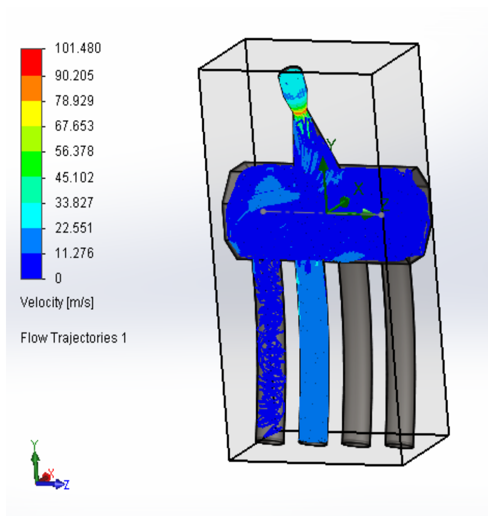

Figure 4.9 Velocity variation in runner3

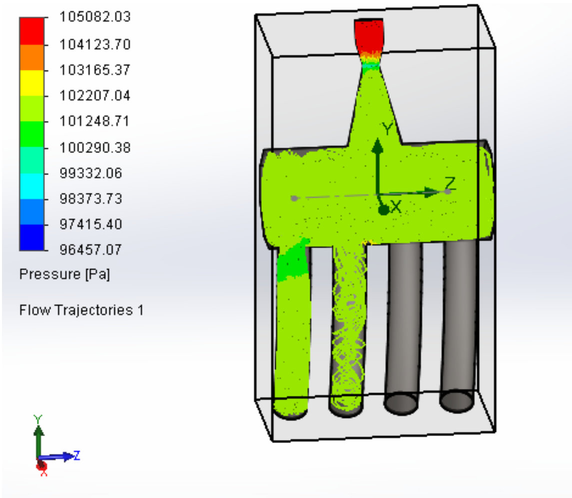

Figure 4.10 Pressure variation in runner4

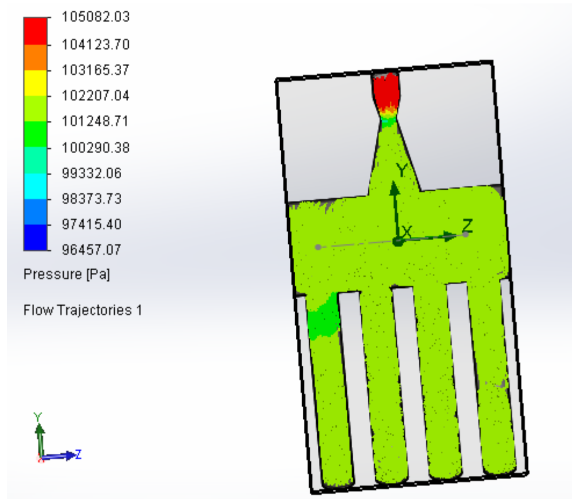

Figure 4.11 Pressure variation in all runners

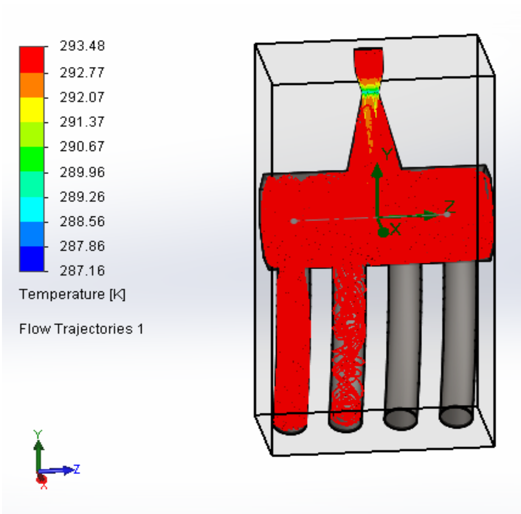

Figure 4.13 Temperature variation in runner4

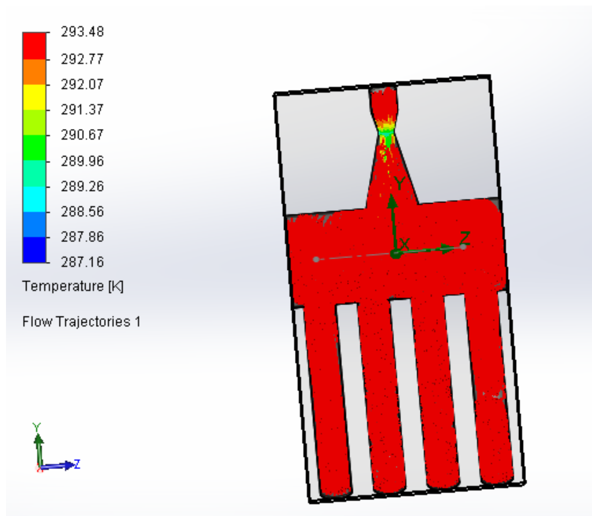

Figure 4.13 Temperature variation in all runners

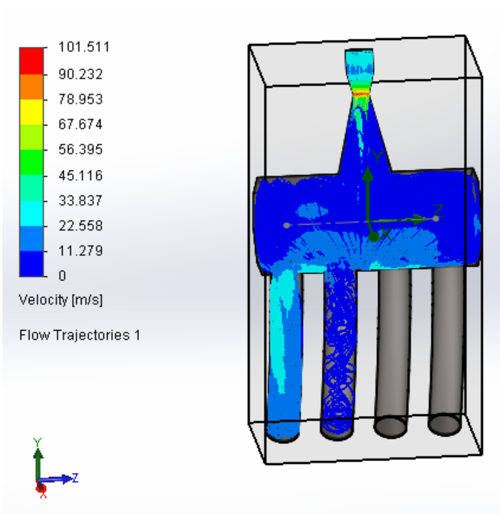

Figure 4.14 Velocity variation in runner4

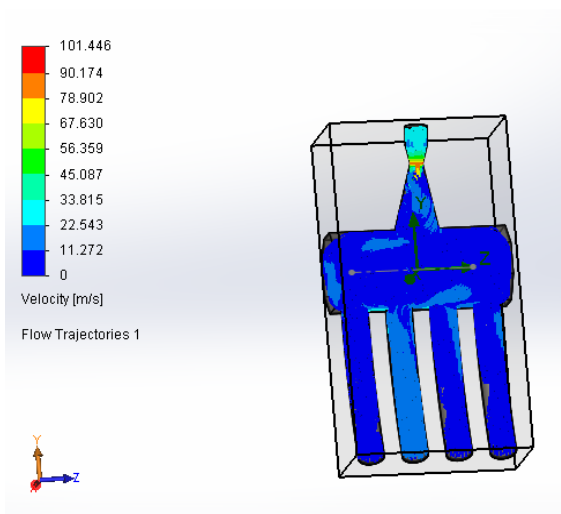

Figure 4.15 Velocity variation in all runners

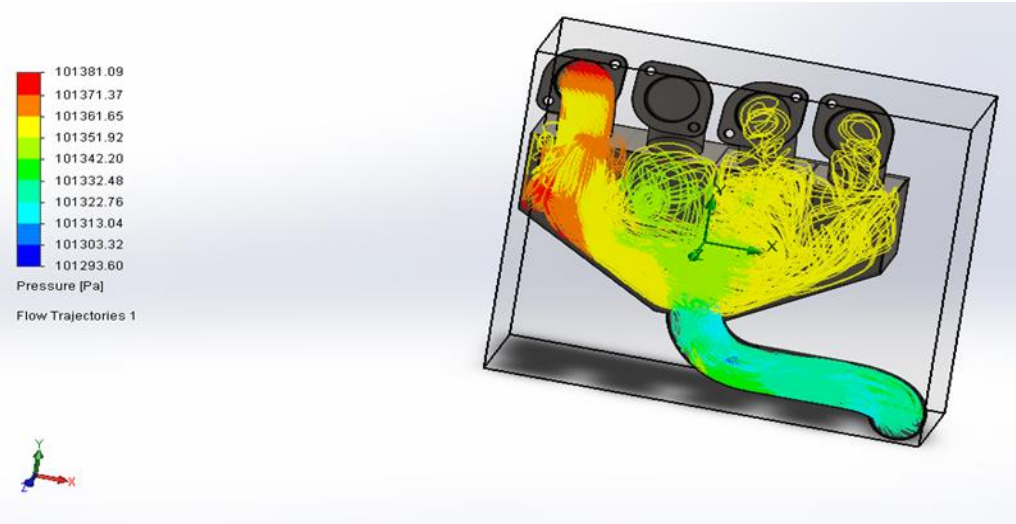

Figure 4.16 Pressure variation in exhaust header when valve 1 opens in model1

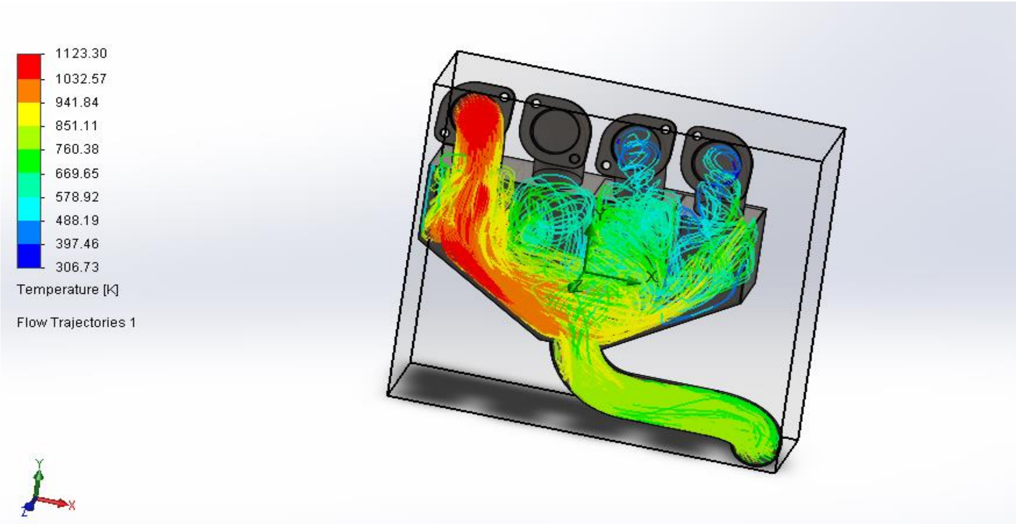

Figure 4.17 Temperature variation in exhaust header when valve 1 opens in model1

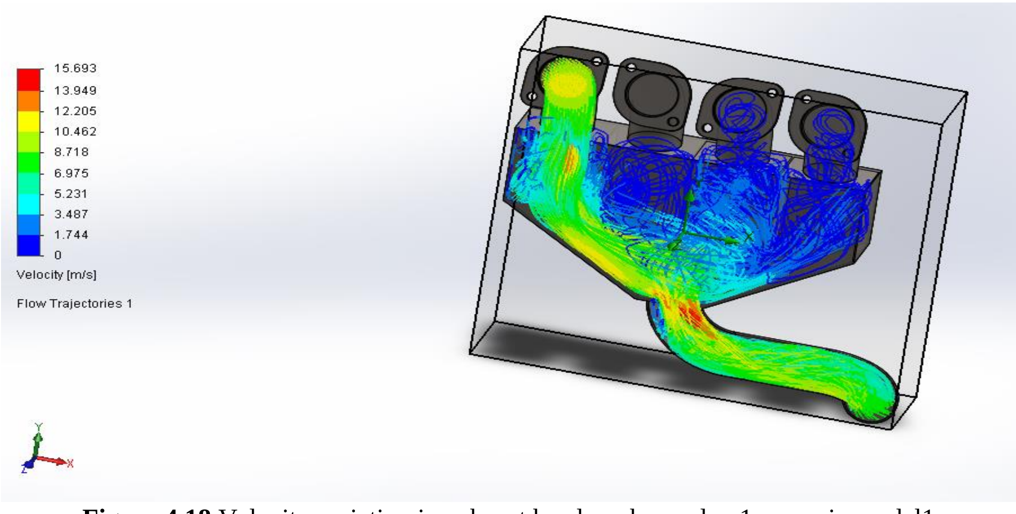

Figure 4.18 Velocity variation in exhaust header when valve 1 opens in model1

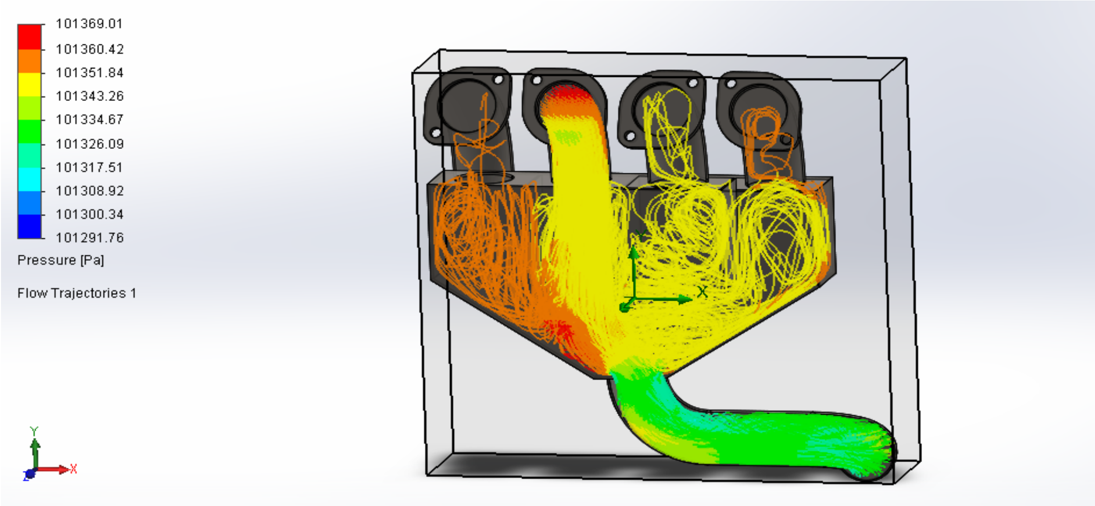

Figure 4.19 Pressure variation in exhaust header when valve 2 opens in model1

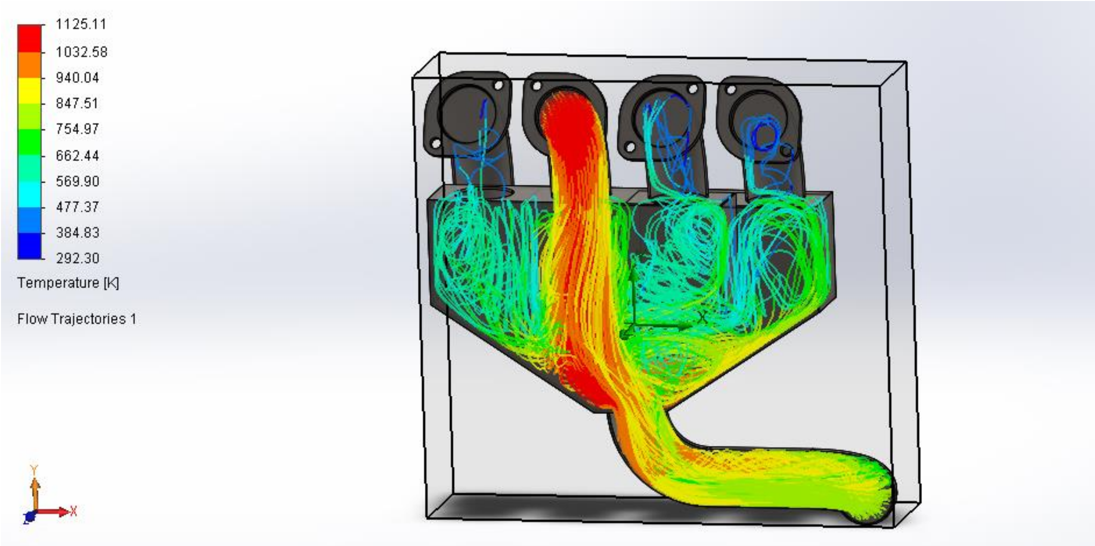

Figure 4.20 Temperature variation in exhaust header when valve 2 opens in model1

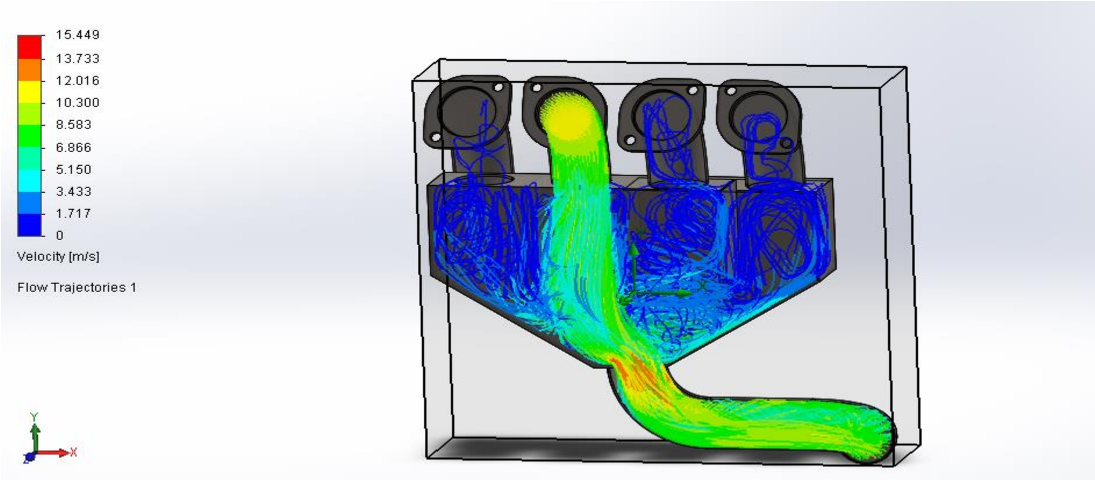

Figure 4.21 Velocity variation in exhaust header when valve 2 opens in model1

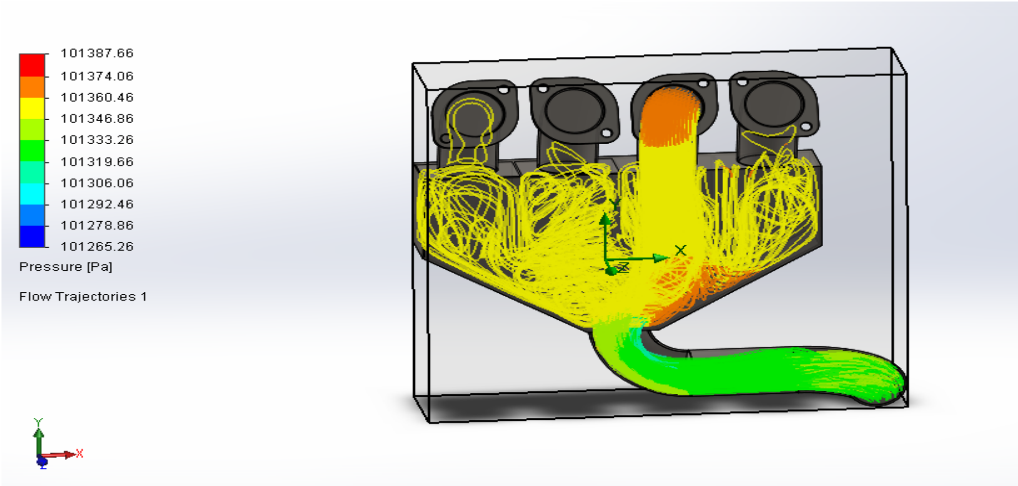

Figure 4.22 Pressure variation in exhaust header when valve 3 opens in model1

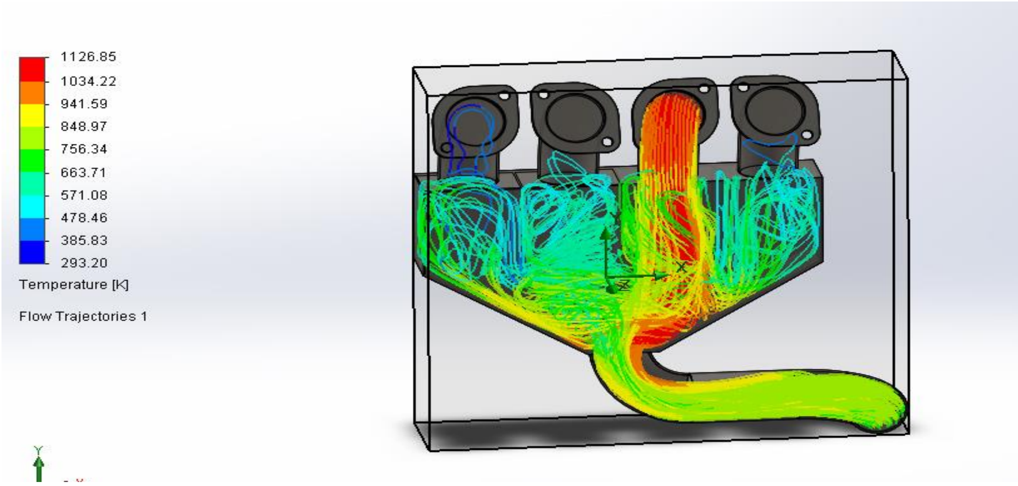

Figure 4.23 Temperature variation in exhaust header when valve 3 opens in model1

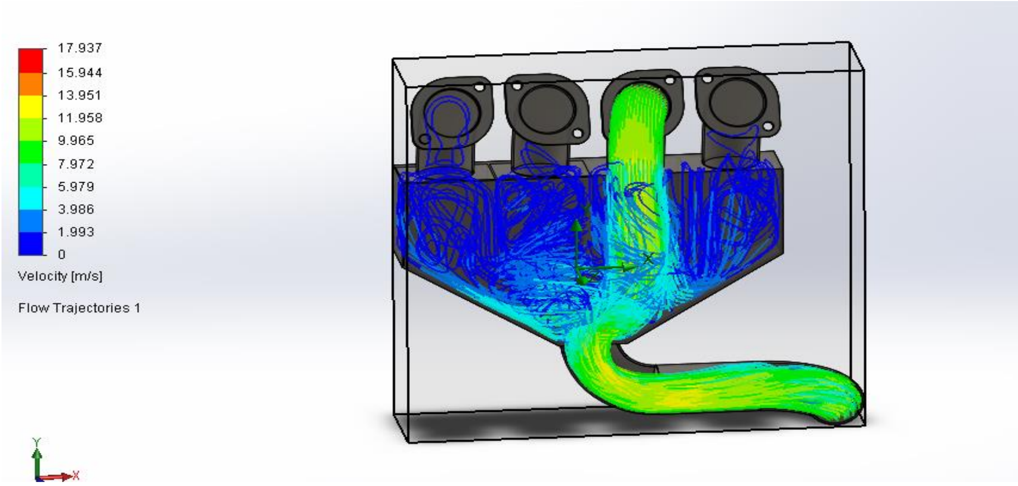

Figure 4.24 Velocity variation in exhaust header when valve 3 opens in model1

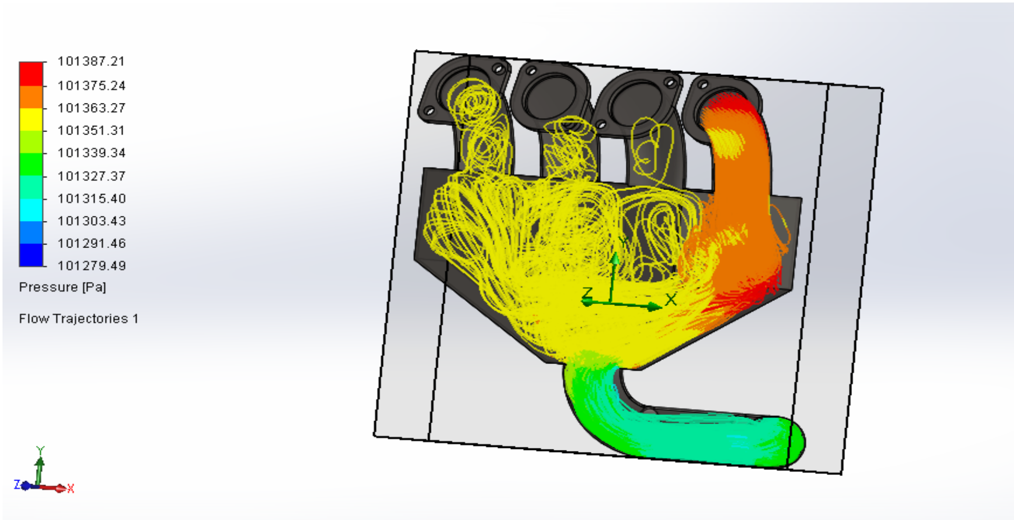

Figure 4.25 Pressure variation in exhaust header when valve 4 opens in model1

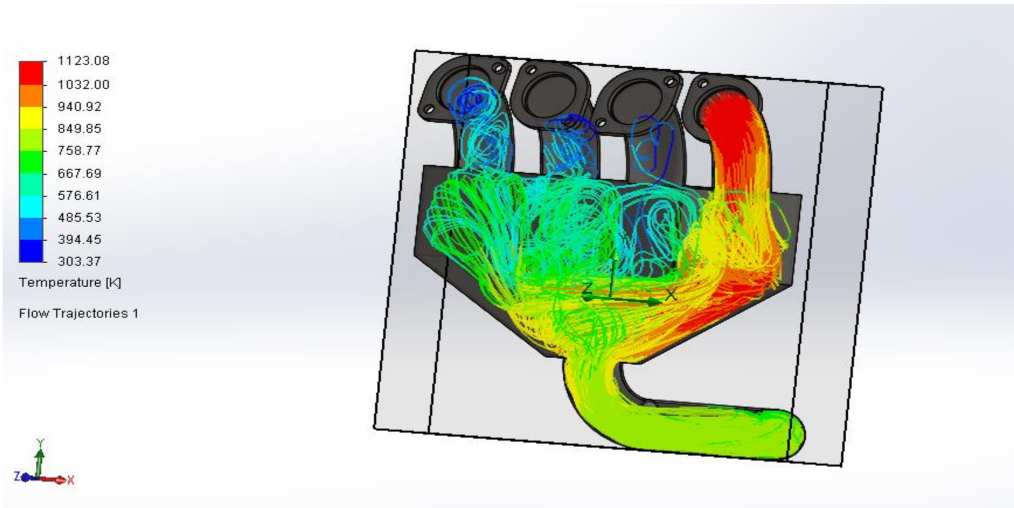

Figure 4.26 Temperature variation in exhaust header when valve 4 opens in model1

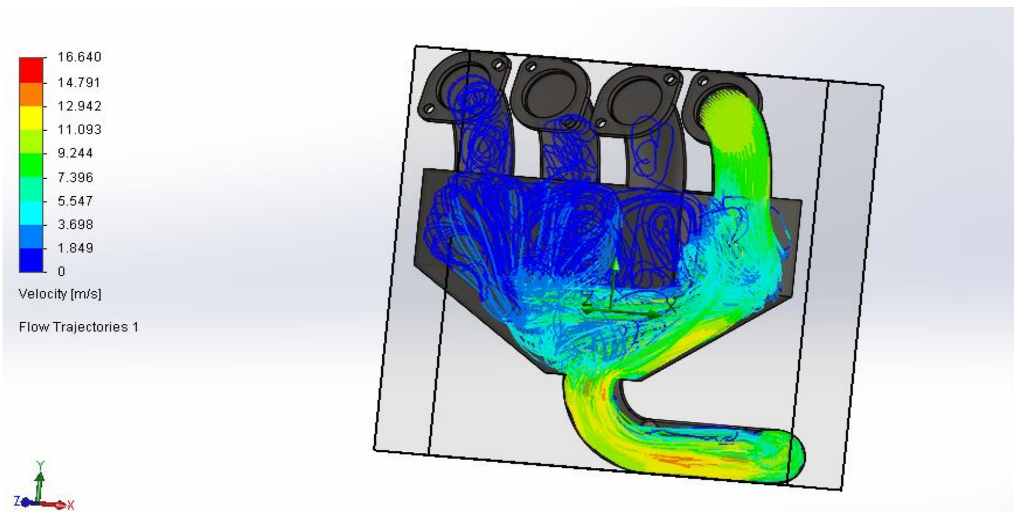

Figure 4.27 Velocity variation in valve 4

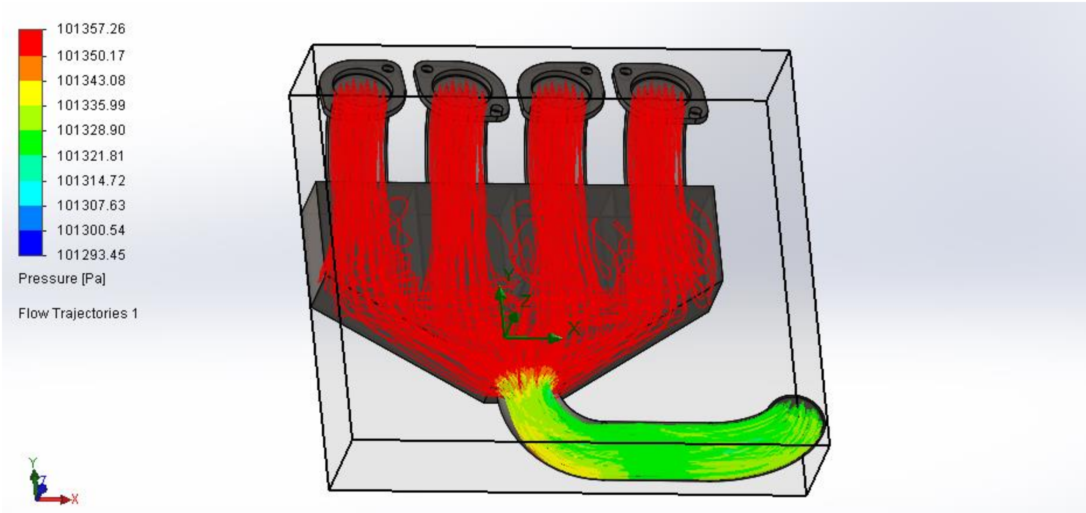

Figure 4.28 Pressure variation in exhaust header in model1

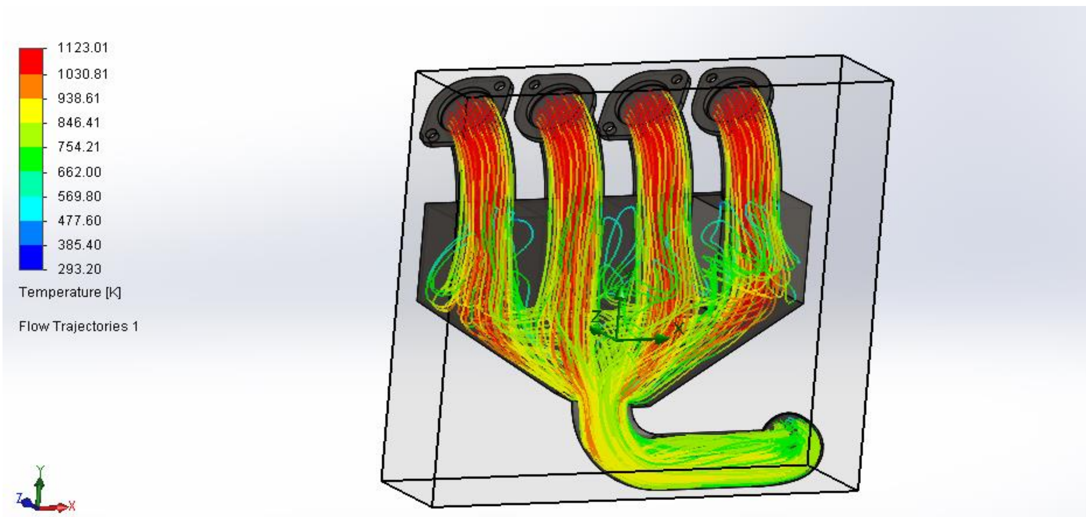

Figure 4.29 Temperature variation in exhaust header in model1

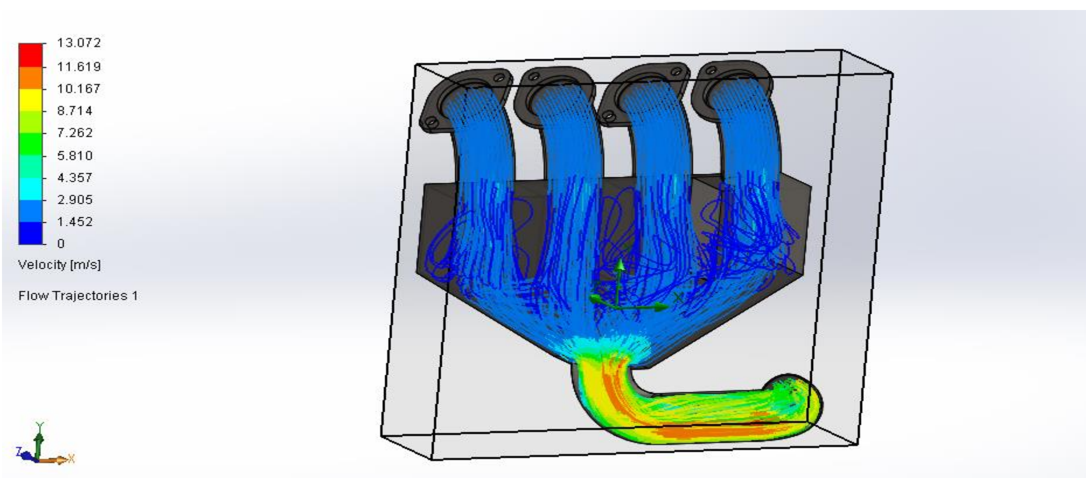

Figure 4.30 Velocity variation in exhaust header in model1

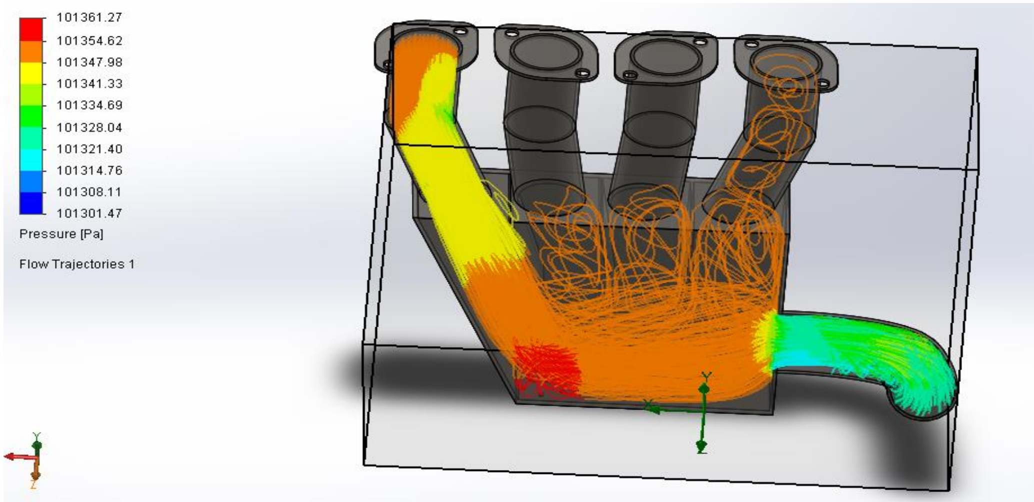

Figure 4.31 Pressure variation in exhaust header when valve 4 opens in model2

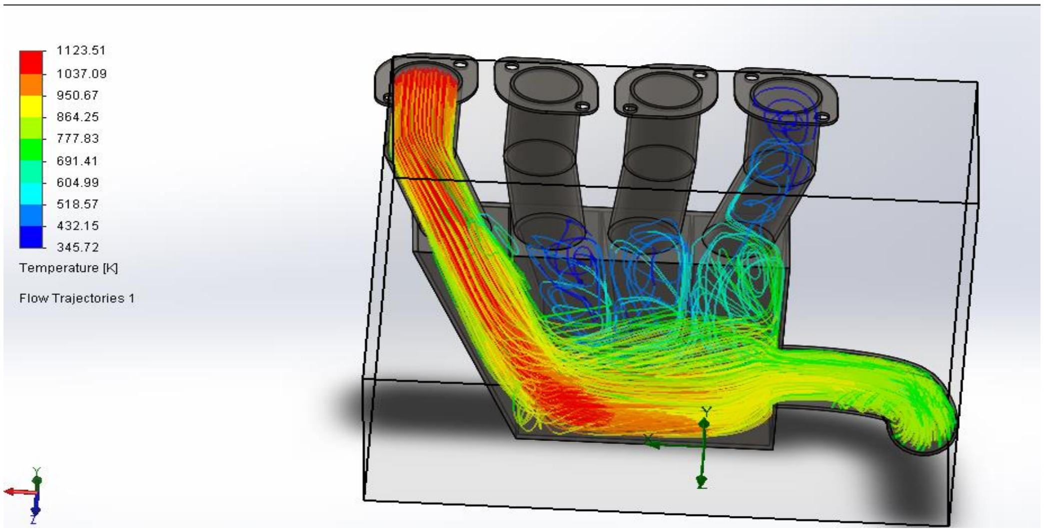

Figure 4.32 Temperature variation in exhaust header when valve 4 opens in model2

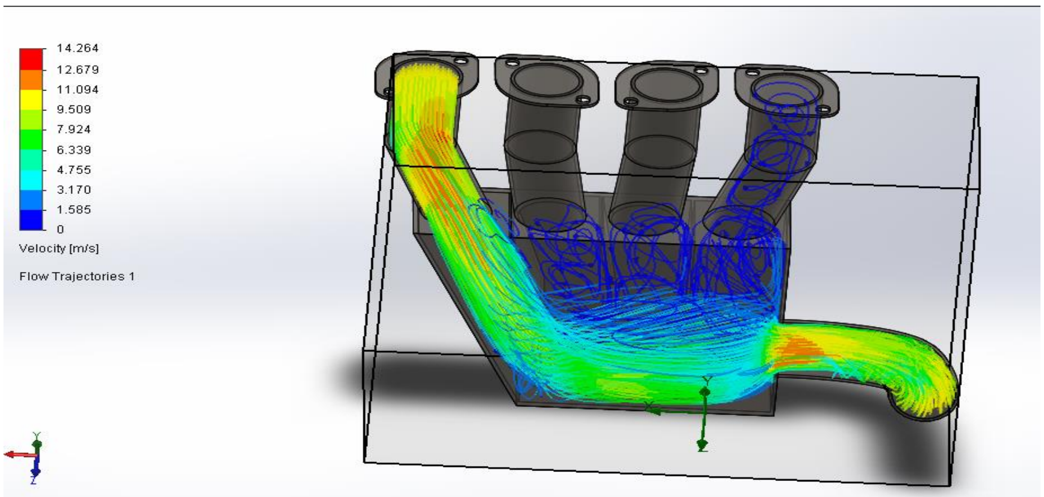

Figure 4.33 Velocity variation in exhaust header when valve 4 opens in model2

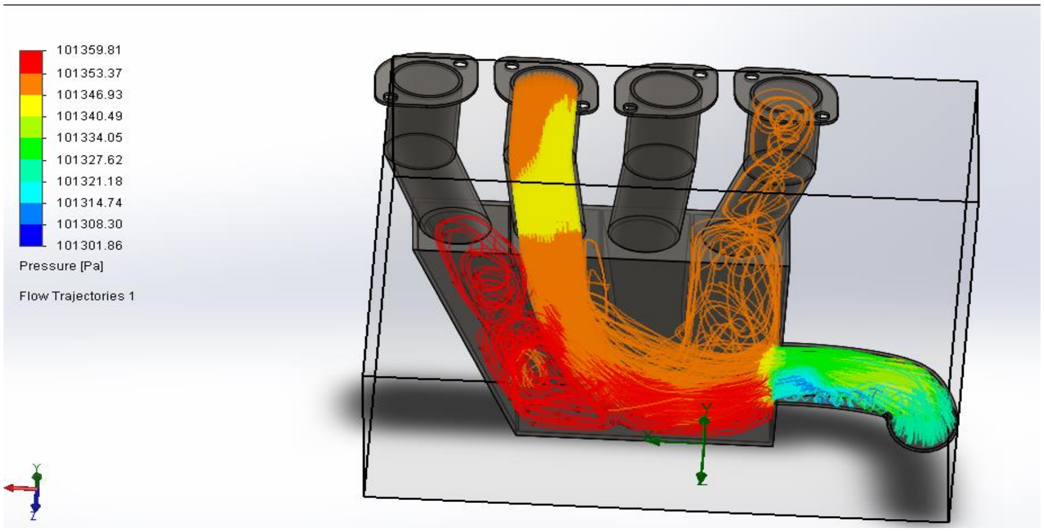

Figure 4.34 Pressure variation in exhaust header when valve 3 opens in model2

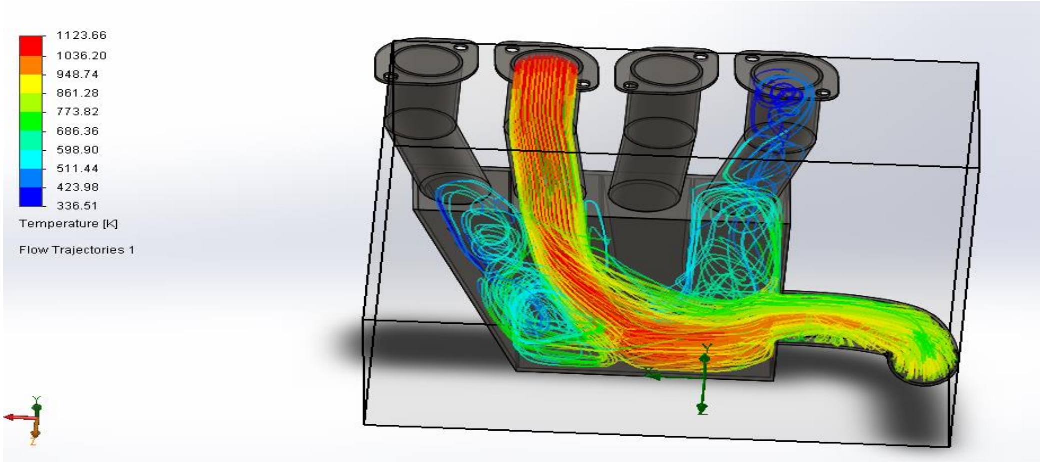

Figure 4.35 Temperature variation in exhaust header when valve 3 opens in model2

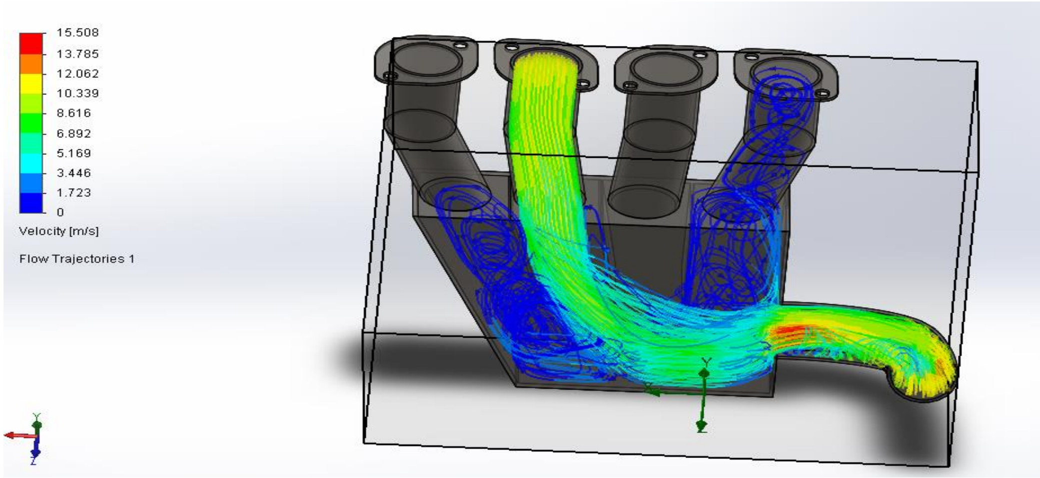

Figure 4.36 Velocity variation in exhaust header when valve 3 opens in model2

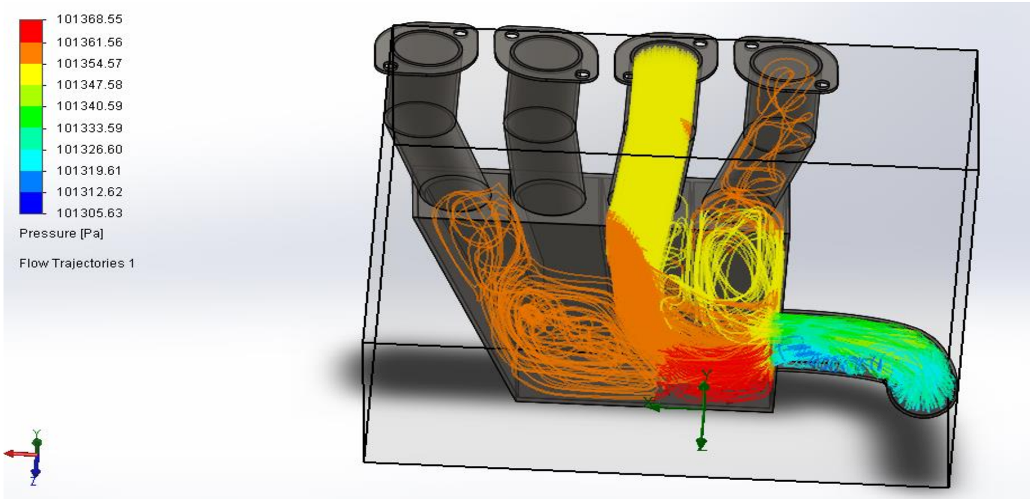

Figure 4.37 Pressure variation in exhaust header when valve 2 opens in model2

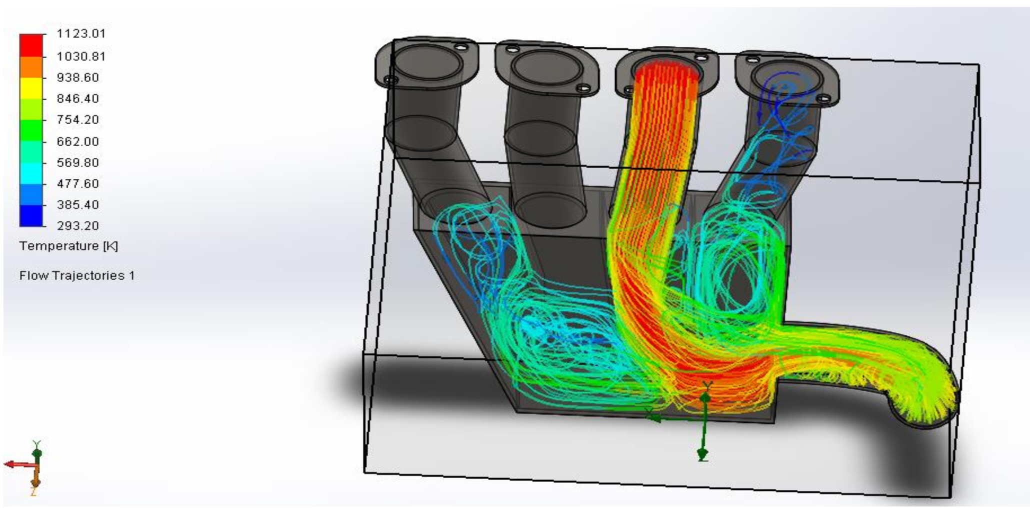

Figure 4.38 Temperature variation in exhaust header when valve 2 opens in model2

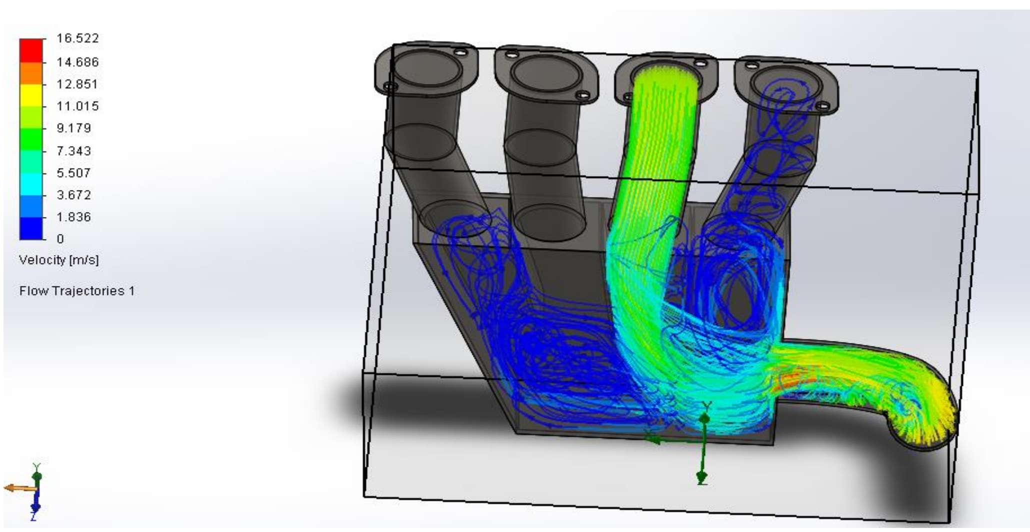

Figure 4.39 Velocity variation in exhaust header when valve 2 opens in model2

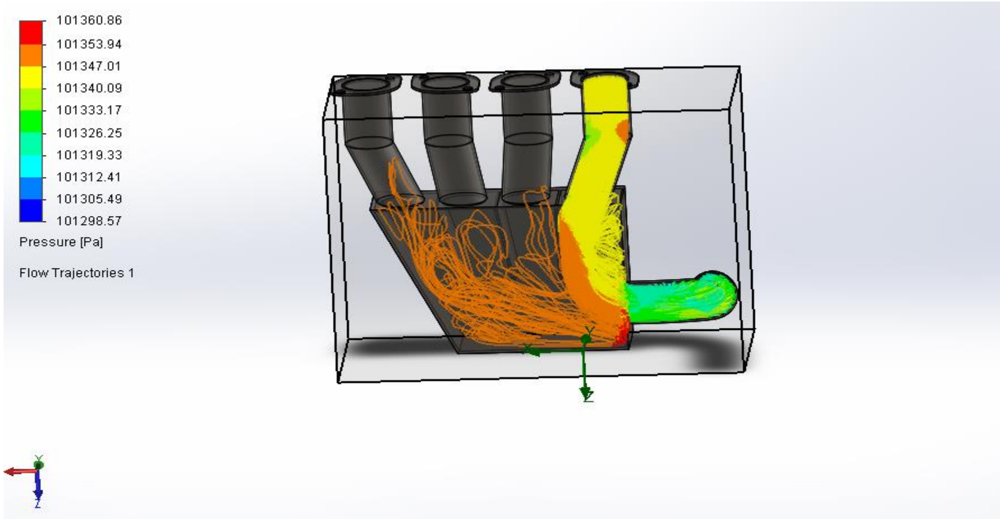

Figure 4.40 Pressure variation in exhaust header when valve 1 opens in model2

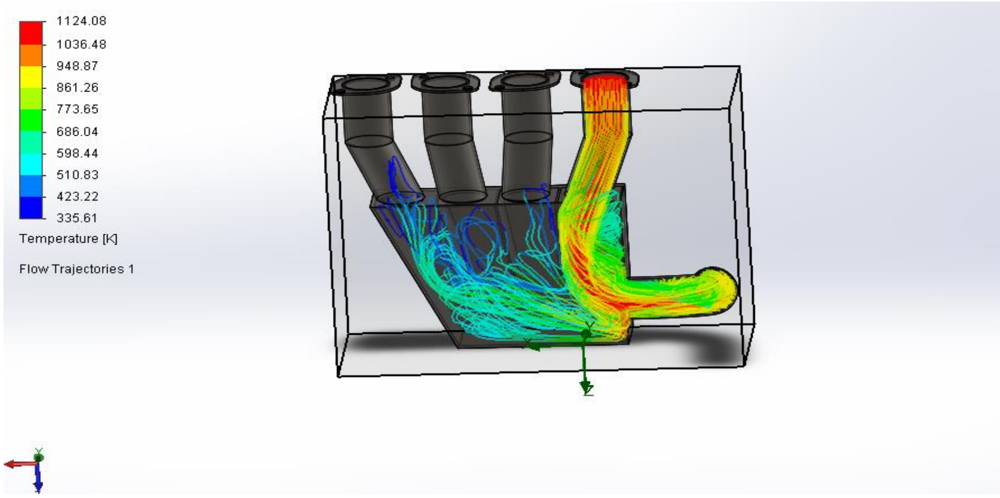

Figure 4.41 Temperature variation in exhaust header when valve 1 opens in model2

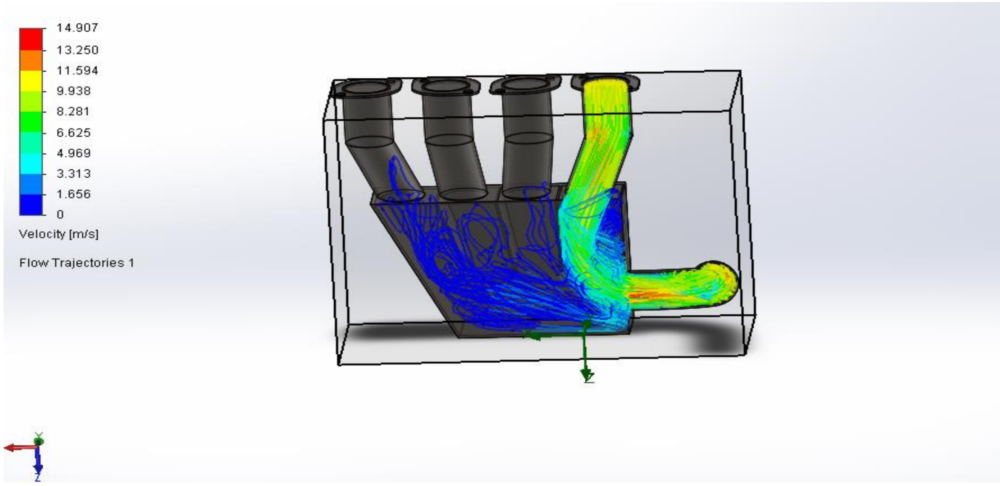

Figure 4.42 Velocity variation in exhaust header when valve 1 opens in model2

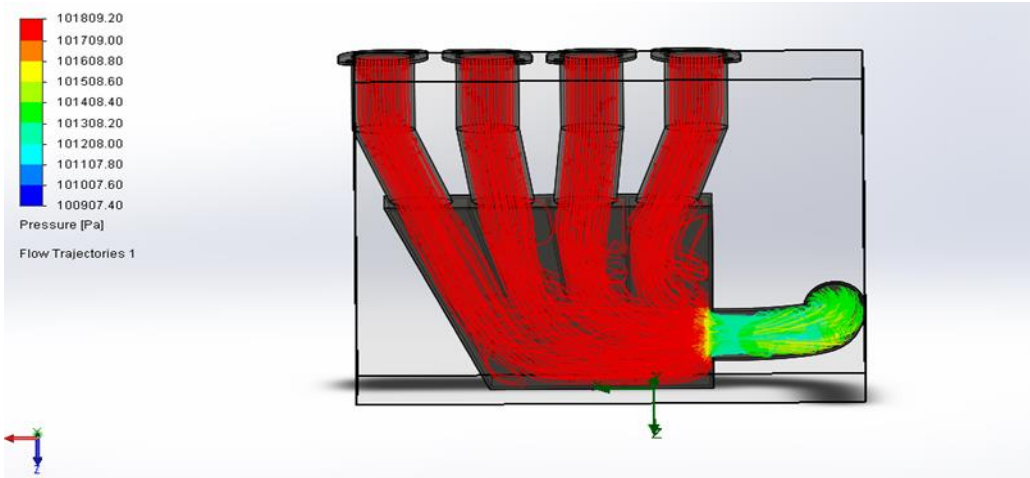

Figure 4.43 Pressure variation in exhaust header in model2

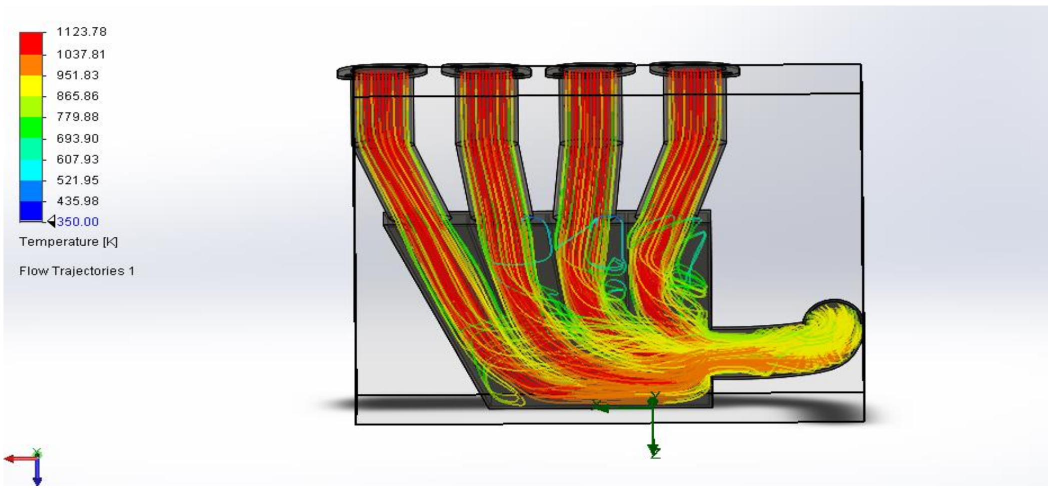

Figure 4.44 Temperature variation in exhaust header in model2

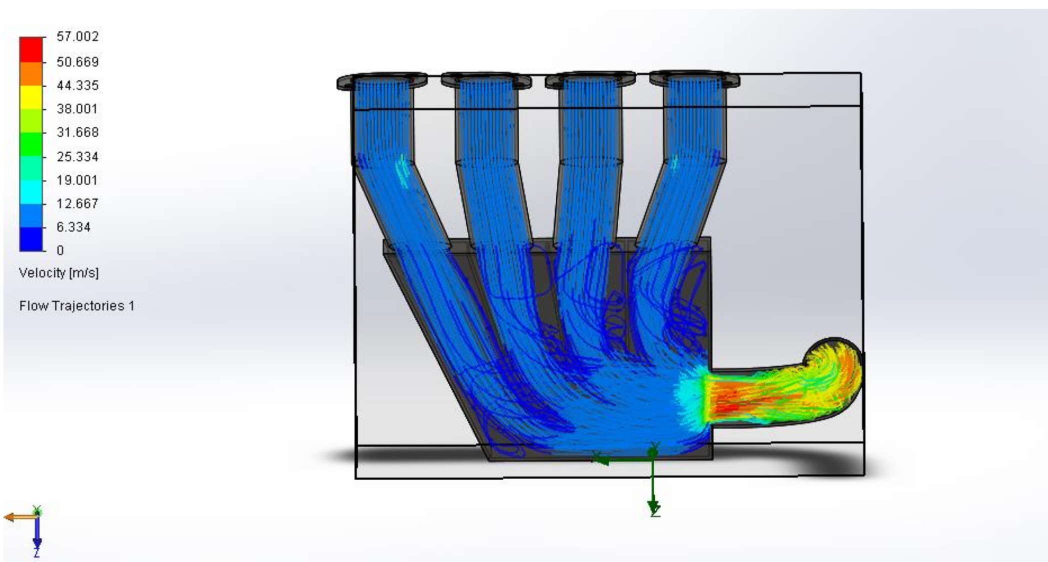

Figure 4.45 Velocity variation in exhaust header in model2

Chapter 5

Closure

5.1 Conclusions

The design was analyzed in CAD software (SOLIDWORKS) and also it was tested practically. Results obtained were satisfactory. The noise test run with the gearbox in neutral at the required engine speed, gave a reading of 103dB and 106dB at approx. 11000rpm which was well within requirements of these competitions. And, it was only basic work a lot of future work was to be done like silencer selection, dyno testing and engine tuning.

5.2 Silencer Selection

The silencer is generally the largest single contributor to exhaust back-Exhaust Systems Application and Installation Guide pressure. Therefore, required noise reduction and permissible backpressure must be considered when selecting a silencer. Application type, available space, cost and appearance may also need to be taken into account.

To select a silencer, use silencer supplier data, corrected for outlet temperature and velocity, to determine the silencer size and type that satisfies noise reduction criteria with an acceptable maximum pressure drop. After calculating pressure loss, it may be necessary to check a second silencer, or a different pipe size, before an optimum combination is achieved. Silencer design is a highly specialized art. Responsibility for the details of design and construction should be assigned to the silencer manufacturer.

5.3 Dyno Testing & Engine Tuning

Engines like the Yamaha YZF R6 used for this project are tuned from the factory to breathe air through 4 x 40 mm diameter throttle bodies. However, after imposing a 20mm diameter restriction for the competition on a single inlet pipe and all air that enters the engine must go through this restrictor. This restriction will not allow the engine to breath according to data supplied by the stock engine control module. Therefore it is necessary to re-tune the engine for new configuration. This was accomplished on the engine by the ECU supplied by performance electronics.

In order to properly tune an electronically fuel injected engine like the Yamaha YZF R6, a large variety of sensors are required. These may be internal or external.

The internal engine sensors are:

a. Cam pulse generator
b. Crank angle sensor

These both internal sensors are Hall Effect sensors. The first one gives the ECU info about engine rpm and the second one gives info about crank shaft rotation.

Other external sensors which play important role in enhancing performance include:

a. sensor (O2)
b. Oxygen Intake air temperature sensor (IAT)
c. Intake manifold absolute pressure sensor (MAP)
d. Throttle position sensor (TP)
e. Exhaust gas temperature sensor (EGT)
f. Engine coolant temperature sensor (ECT)

These sensors are either required for monitoring engine condition while running or for tuning of the engine performance.

5.4 Future Scope:

This design was solely based on taking consideration of manufacturing issue and was cost efficient. But designed could have been better if sufficient resources. Involvement of ceramic materials in future will help in extra weight reduction and better performance. A rapid proto type model or reinforced fiber would be a better solution rather than using metal. For exhaust system instead of using stock muffler of any other vehicle a new muffler can be design with an expansion chamber with sound absorbing material in the cavity.

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